Landscape evolution under different IPCC RCP warming scenarios at the Canning River, Alaska.

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1 Introduction

The arctic is rapidly warming past the global mean temperature increase as a result of polar amplification (*Manabe and Stouffer*, 1980; *Holland and Bitz*, 2003). One way a rapidly warming climate system impacts terrestrial systems by increasing active layer thickness (ALT) in permafrost regions (*Romanovsky and Osterkamp,* 1998) and by influencing thermally insulating snowpack (*Walvoord and Kurylyk*, 2016). Structural knowledge of permafrost is the first step in constraining the fluxes of mobile soil species to the atmosphere.

Understanding and constraining the carbon contributions to the atmosphere as a result of the changing arctic terrestrial systems is one of the most important and least understood portions of our climate future (*Hugelius et al.*, 2014). Increasing ALT in permafrost enables increased soil diffusion which in turn will affect the mobilization and burial of particulate organic matter (*Hilton*, 2015). In this report, I present a first-order attempt to model the amount of diffusion of soils in the Canning River area in Northern Alaska in four different IPCC warming scenarios.

2 Study Area

The study area of choice is the point of intersection between the Brooks Range and the Canning River, Alaska represented by the polygon with coordinate vertices at (70.08425 N, 147.46630 W), (69.74381 N, 147.52742 W), (70.03636 N, 145.77403 W), and (69.70361 N, 145.85364 W). The Brooks Range is expected to produce an increasing amount of sediment due to ongoing deglaciation (*Lamb and Toniolo*, 2016). In the region between the Brooks Range and the Beaufort Sea, increasing global temperatures have been associated with increased ALT in permafrost (*Hinzman et al.*, 2005). The selection presented here is to serve as the compromise between the two regions.

A digital elevation model for the study area was retrieved via the Arctic DEM explorer (https://livingatlas2.arcgis.com/arcticdemexplorer/) (*Porter et al.*, 2020). An image of the study area can be seen below in Figure 1:

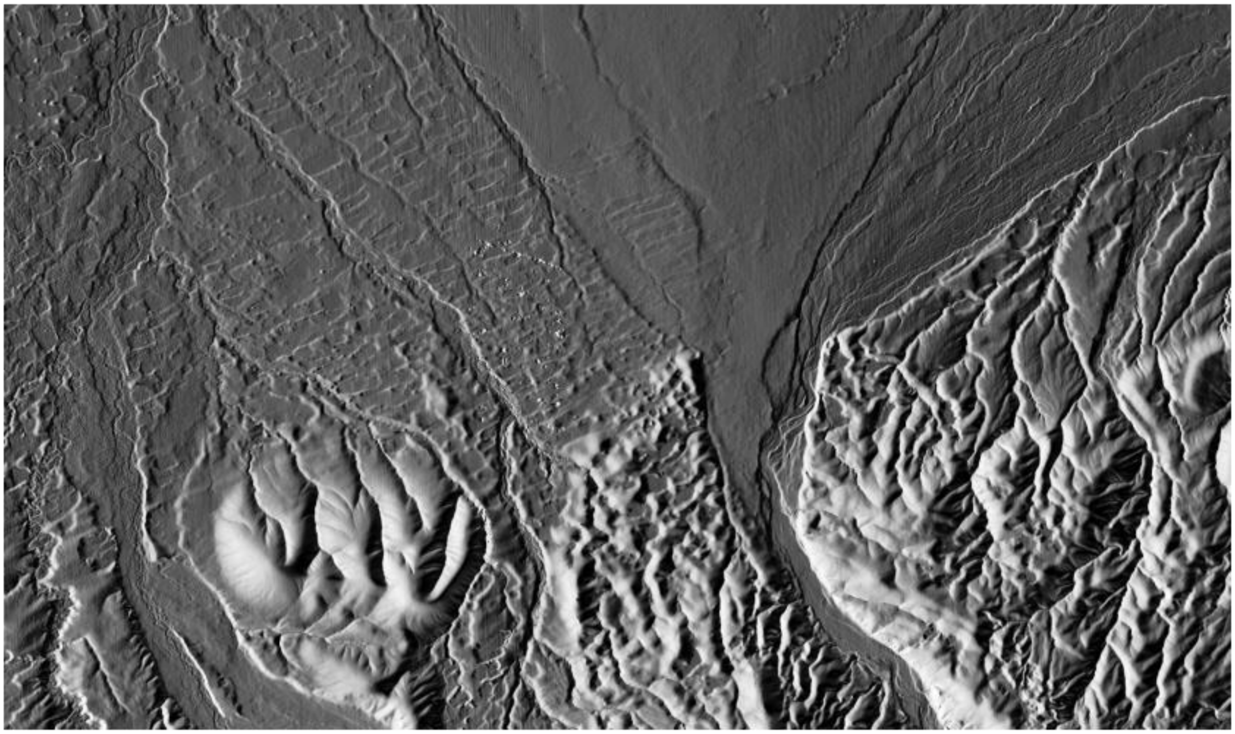

Figure 1: Canning river DEM visualization

3 Methods

In order to appropriately simulate soil diffusion, ALT must be estimated over time scales of soil diffusion. A 1D Kudrayavtsev model was selected to achieve this (*Anisimov et al.*, 1997, *Sazonova and Romanovsky*, 2003). This model is driven by air temperature, snow cover, vegetation, soil moisture, soil thermal properties and outputs annual mean soil temperature and mean ALT annually. Recent studies documenting sensitivities of the Kudrayatsev model show the air temperature is a primary source of variability and thus was chosen as the parameter of interest for this study (*Wang et al.*, 2020). To approximate mean annual air temperature at the Canning River/Brooks Range sample site, an analogous site was selected, Sag1 MNT, located at 69.43 N, 148.67 W (*Wang et al.*, 2018). Approximate values for permafrost are used for other input values following direct communication with Irina Overeem.

In order to apply the Kudrayatsev model to a landscape evolution model, Landlab was used. Landlab is a modeling library which incorporates numerical spatial techniques to evaluate earth systems processes (*Hobley et al.*, 2017, *Barnhart et al.,* 2020). The spatial discretization is done by a raster grid (function RasterModelGrid) of the dimensions of the Canning River DEM. Soil diffusion is done by Landlab function DepthDependentDiffuser in the style of *Johnstone and Hilley* (2015). Hillslope sediment flux is then determined by:

$$q_s = -DSH^*(1.0 - exp(-H/H^*)$$

Equation 1: Hillslope sediment flux

Where D is a linear soil diffusivity, S is slope, H is effective soil depth, and H* is the soil decay depth. D and H* and highly dependent on the lithology of the system (J*ohnstone and Hilley,* 2015). For this reason, token values of 1 x 10^{-2} m^2/y and 1 m were used for D and H* respectively. S is determined by the gradient between raster grid heights. H is the Kudrayatsev model-determined ALT. Depth-dependent diffusion was run in single year time steps.

Four different temperature warming scenarios were considered for the four different representative concentration pathways (RCP) published with the IPCC fifth Assessment Report (2014). The pathways, RCP2.6, RCP4.5, RCP6, and RCP8.5, detail differing anthropogenic emission contributions projected out to the year 2100 CE. Linear temperature profiles were created using the last 35 years of change and expanded out 300 years for input for the Kudrayatsev model. Slopes for individual situations can be seen below in Table 1:

Scenarios	Determined Slope (°C/year)
RCP2.6	~0
RCP4.5	0.0114
RCP6	0.0257
RCP8.5	0.0486

Table 1: Determined linear temperature gradients from the IPCC fifth Assessment Report's RCP scenarios.

4 Results

The Kudrayatsev model was simulated for 1000 years which enables observation of periods when the average annual soil temperature becomes above the freezing point of water. The results of all four RCP scenarios can be seen in Figure 2:

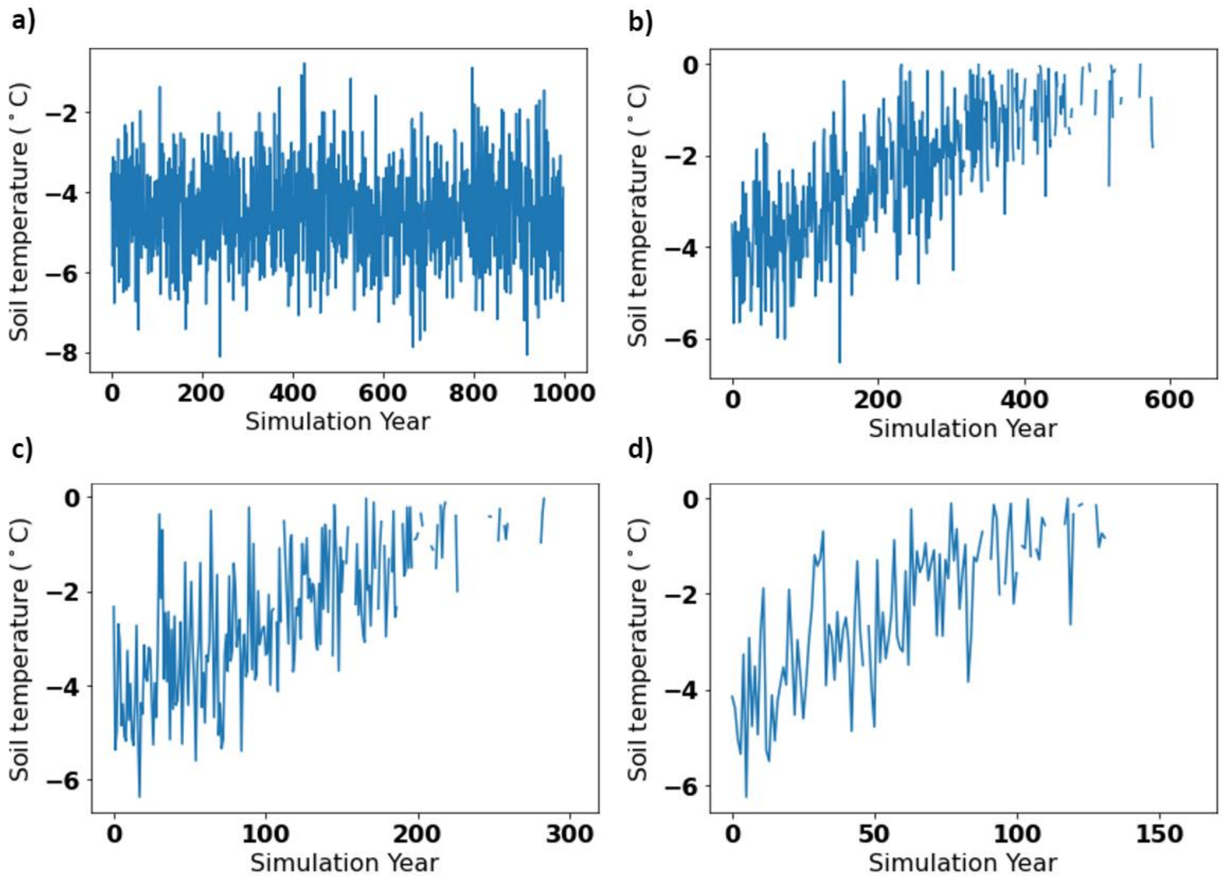

Figure 2: Average annual soil temperature for the four RCP scenarios a) RCP2.6, b) RCP4.5, c) RCP6, and d) RCP8.5. When the annual soil temperature is above 0°C no value is printed. Truncated time domains indicate that no more following values ever dropped below 0°C.

Likewise, ACT was determined for the time period as well. Though not plotted, the excluded values represent the years where average annual soil temperature was above 0°C.

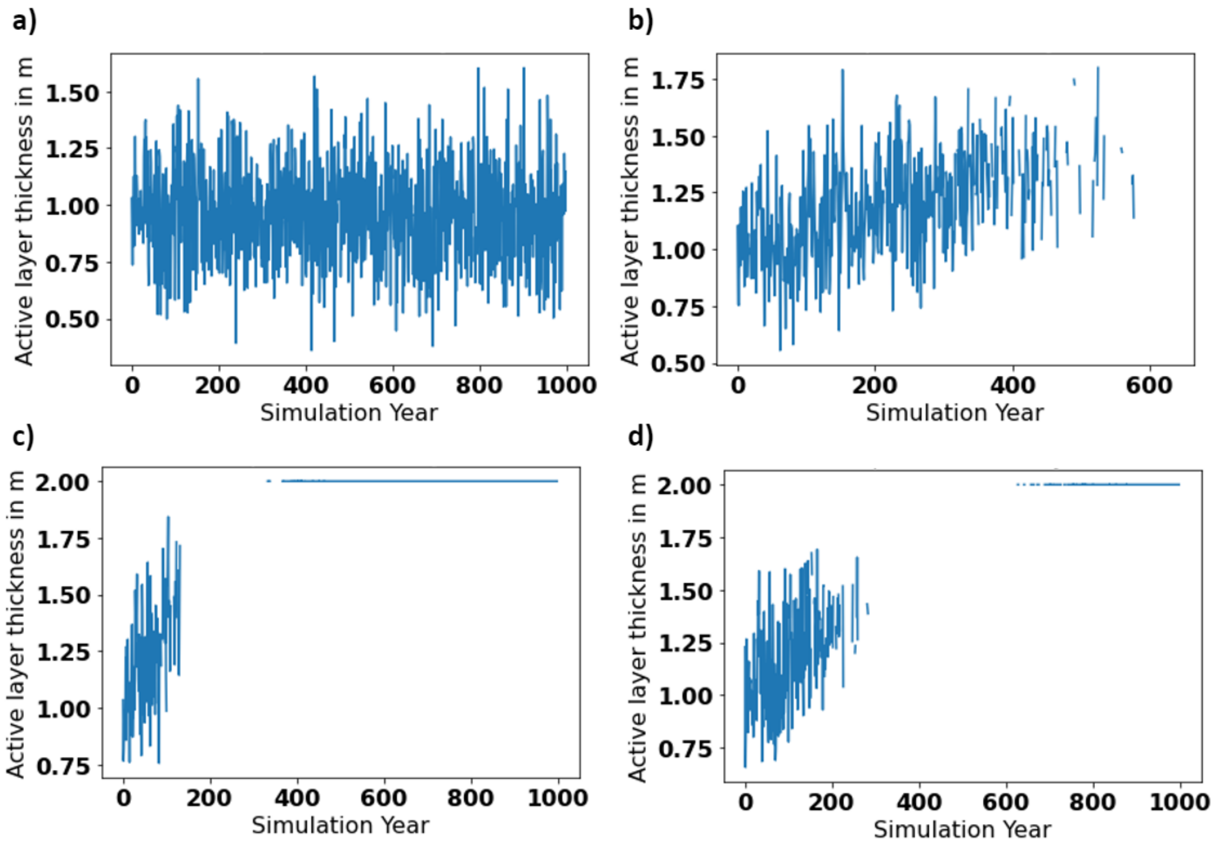

Figure 3: Active layer thickness for the four RCP scenarios a) RCP2.6, b) RCP4.5, c) RCP6, and d) RCP8.5. When the annual soil temperature is above 0°C No value is printed. Top values shown indicate model breakdown.

Hillslope soil diffusion was done for 300 years as a result of the observation that under three of the four RCP scenarios, annual soil temperature would rapidly exceed the freezing point of water within the study area. Using the difference of the initial DEM to the resulting DEM, the elevation change can be established. The result ended up being functionally invariant of the

ACT. The resulting elevation change for all RCP scenarios is below in Figure 4:

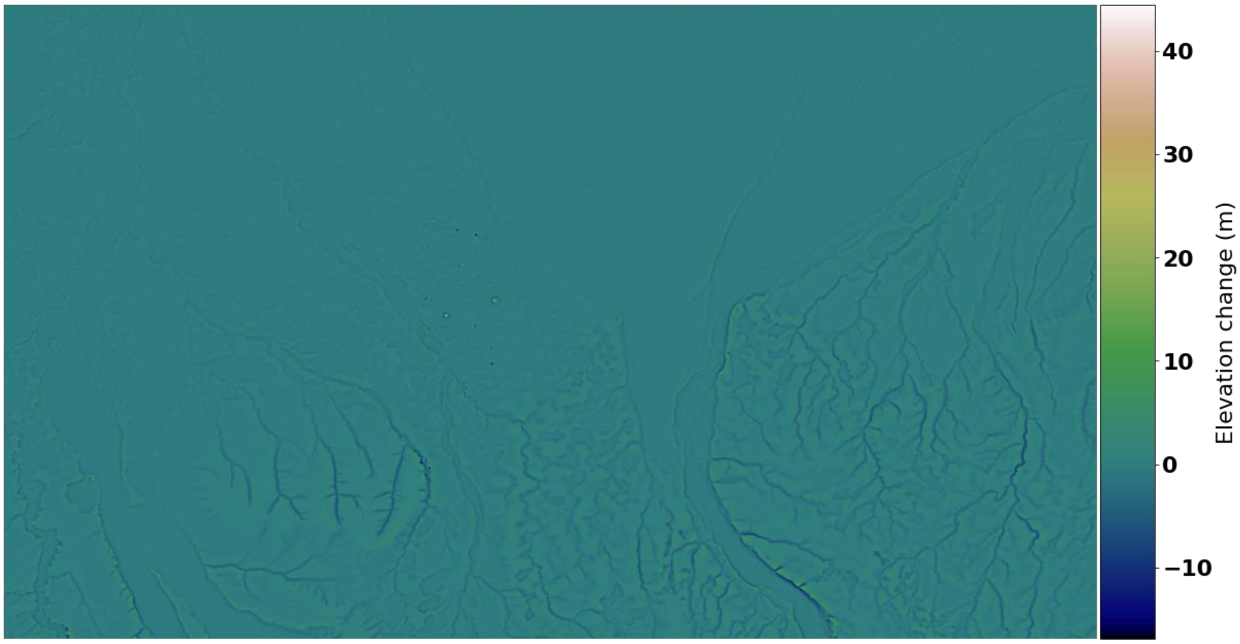

Figure 4: Example sample net elevation change for 300 years of soil diffusion in the study area.

5 Discussion

The Kudrayatsev model is ill-equipped to simulate sub-annual change when the annual average soil temperature exceeds 0°C. It is likely that permafrost collapse effectively happens at this point though it should be noted that permafrost collapse is a complicated topic that requires more area specific knowledge outside the scope of this study. Permafrost collapse also happens at different time scales, some cases occurring at finer resolution than used in this study (*Turetsky et al.*, 2019). The specific years where annual average soil temperature exceeds 0°C could be thought of an increasing risk factor for collapse though significantly more study should be done.

There are significant gaps in observational knowledge of the Canning River with regards the parameters not explored in the study: snow cover, vegetation, soil moisture, and soil thermal properties. Future studies would prioritize closing this observational gap and develop methods for projecting what these values will be in the future.

Global air temperature averages will not represent regional changes due to the climate asymmetry from polar amplification (*Manabe and Stouffer*, 1980; *Holland and Bitz*, 2003). As a result, the used air temperature input may not be an accurate representation of each RCP projected climate system. Additional parameters may be likewise changed by polar amplification such as those that end up most affected by precipitation.

Hillslope diffusion-affected elevation ended up being invariant for all RCP scenarios. This could be due to several reasons. First is that default values were used for both diffusivity and soil decay depth. These values are lithology dependent (J*ohnstone and Hilley,* 2015), leaving another observational gap for the study area. Permafrost soil diffusivity maybe be especially different than temperate soils (*Frederick et al.*, 2016).

The second reason is the locality of the ALT parameter. ALT is assumed to be global over the spatial domain when it is certainly not. A 2D Kudrayatsev model mapped to the study area would enable additional constraints that could show variability between different RCPs in more climate sensitive areas of the space. Significant additional work needs to be done to appropriate approximate soil hillslope diffusion in permafrost areas.

6 References

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